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ISD

New Design Approach for Axially Compressed Composite Cylindrical Shells combining the Single Perturbation Load Approach and Probabilistic Analyses

March 25, 2015

DESICOS Conference on Buckling and Postbuckling Behaviour of Composite Structures, Braunschweig

Alexander Meurer, Mona Dannert and Raimund Rolfes

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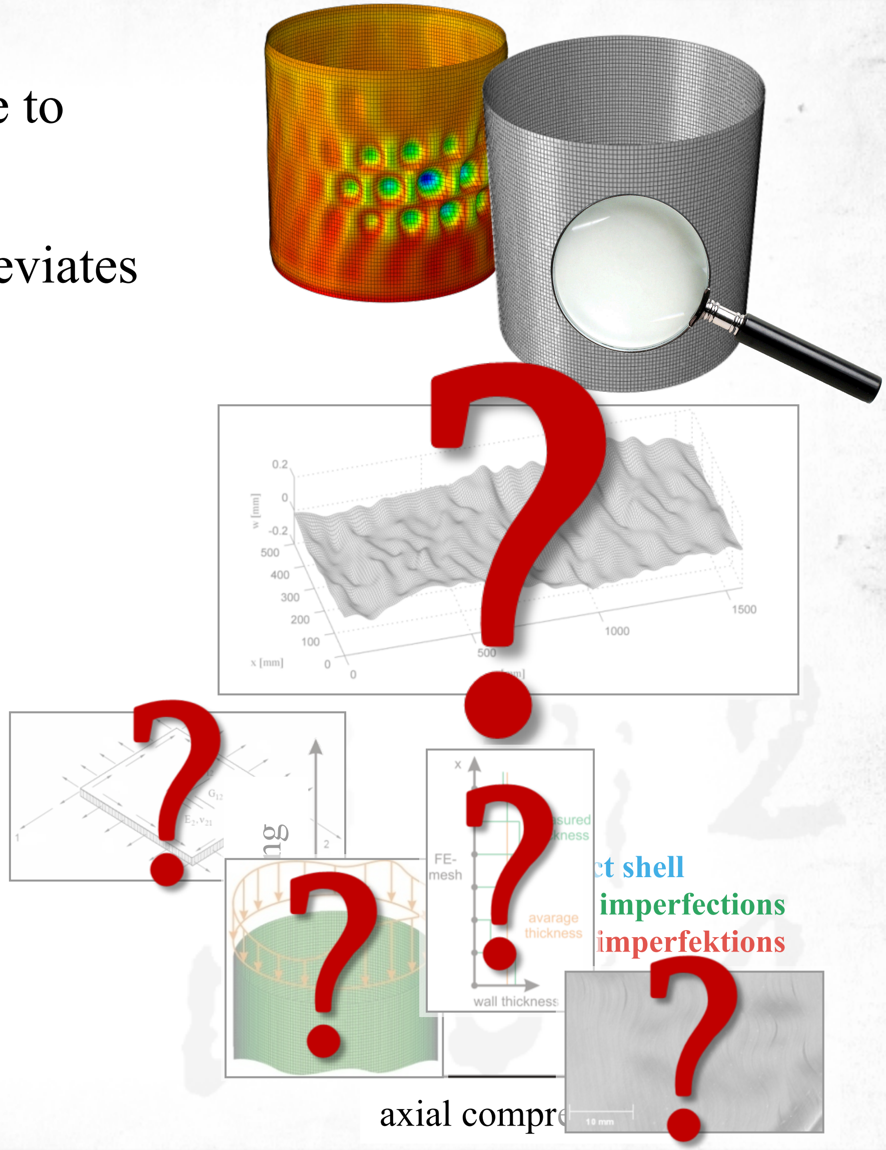
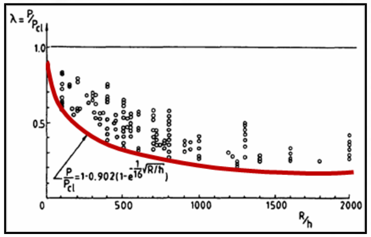
Introduction

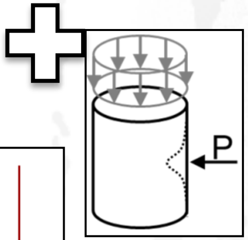
- Axially compressed cylinders are prone to buckling
- A real manufactured cylinder always deviates from the nominal structure
- These imperfections heavily affect the buckling load
    - traditional imperfections
    - non-traditional imperfections
        - material imperfections
        - uneven loading
        - thickness imperfections
        - ...
- Main problem in design: Imperfections are not known prior to manufacturing!

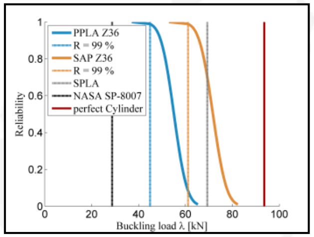


Overview

- Introduction
- Design philosophies
- The “Probabilistic Perturbation Load Approach” (PPLA)
  - Semi-Analytical Probabilistic Procedure (SAP): Overview
  - PPLA: Main idea
  - Application to DESICOS use cases
  - Comparison to other design procedures
- Conclusion and next steps



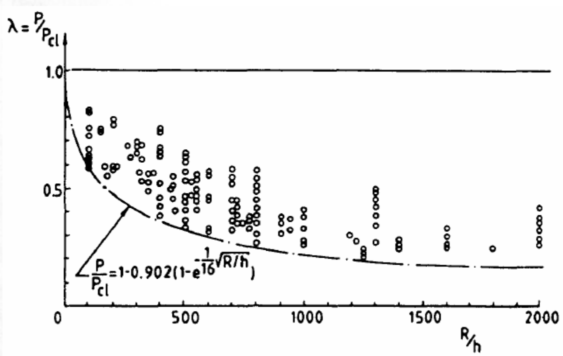




Design philosophies

Knock-Down-Factors

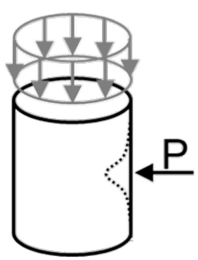
- NASA SP-8007

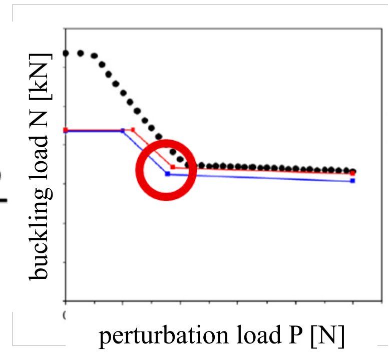


- based on buckling experiments
- in most cases overly conservative
- only partly applicable to composites

Deterministic Design

- Single Perturbation Load Approach (SPLA)



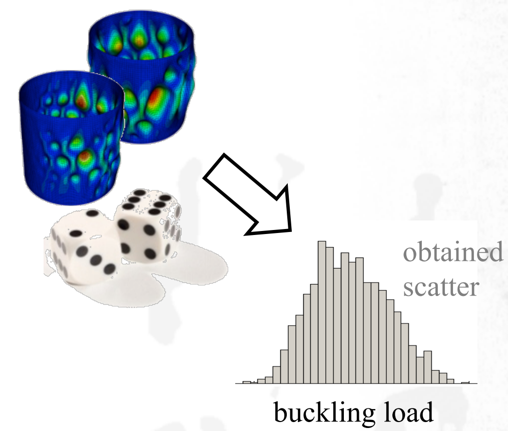


[Hühne et al., 2008]

- no imperfection information necessary
- not always robust (with respect to the experimental buckling loads)

Probabilistic Design

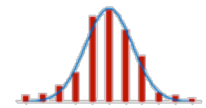
- Monte Carlo
- Semi-analytical procedures



- known level of reliability
- imperfection information necessary
- Monte Carlo computationally costly

Design philosophies

- Qualities of desired design procedure
  - no geometric imperfection information necessary
  - incorporate scatter of non-traditional imperfections
  - always robust

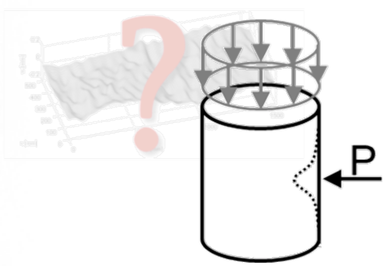


- Combination of

Deterministic Design and Probabilistic Design

geometric imperfections

scattering non-traditional imperfections



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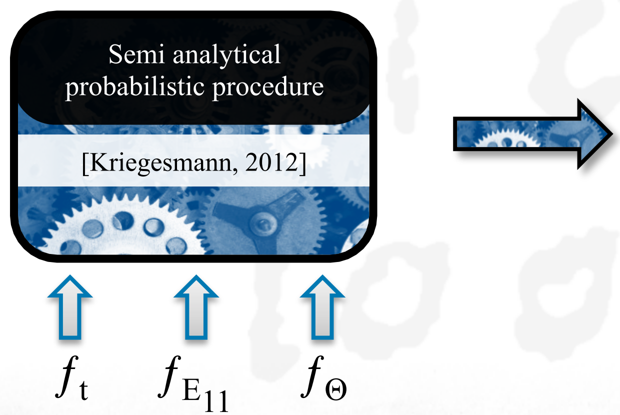


λ_d

Semi-Analytical Probabilistic Procedure (SAP)

[Kriegesmann, 2012]

- Taylor approximation of the objective function
  (= buckling load depending on scattering imperfections)

$$g(\boldsymbol{x}) = g(\boldsymbol{\mu}) + \sum_{i=1}^{n} \frac{\partial g(\boldsymbol{\mu})}{\partial x_i}(x_i - \mu_i) + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{\partial^2 g(\boldsymbol{\mu})}{\partial x_i \partial x_j}(x_i - \mu_i)(x_j - \mu_j) + \dots$$

↳ Mahalanobis transformation to reduce and decorrelate the input parameters

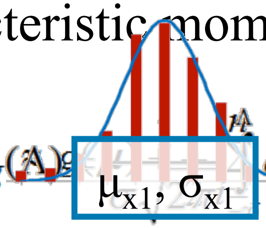
$$\mathbf{x} = \boldsymbol{\Sigma}^{\frac{1}{2}}\mathbf{z} + \boldsymbol{\mu} \quad \text{and} \quad \mathbf{z} = \boldsymbol{\Sigma}^{-\frac{1}{2}}(\mathbf{x} - \boldsymbol{\mu})$$

- Evaluation of the objective function around the mean values of the input parameters
- Numerical determination of the characteristic moments

$$\left(\frac{\partial g(\boldsymbol{\mu})}{\partial z_i}\right)^2 \mathrm{var}(Z_i)$$

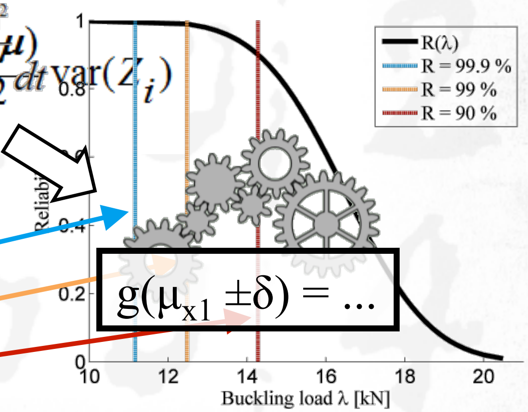
- Choice of a type of distribution
  (i.e. normal distribution)

$$F_g(\lambda) = \dots e^{-\frac{(t-\mu)^2}{2\sigma^2}} dt$$



- Choice of a level of reliability to obtain a robust design load

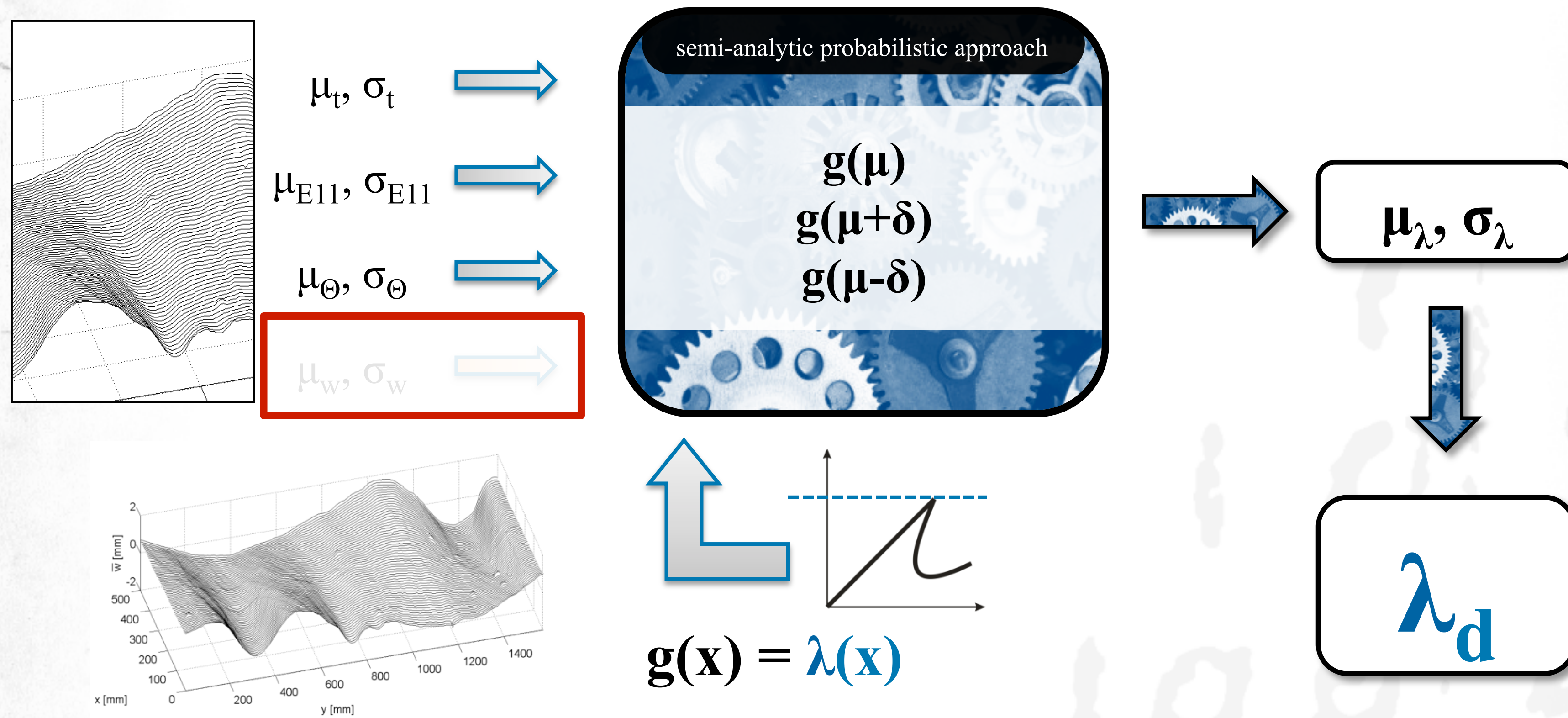
Reliability
99.9 %
99 %
90 %



Probabilistic Perturbation Load Approach (PPLA)

Main idea:

- Combination of probabilistic and deterministic design approaches



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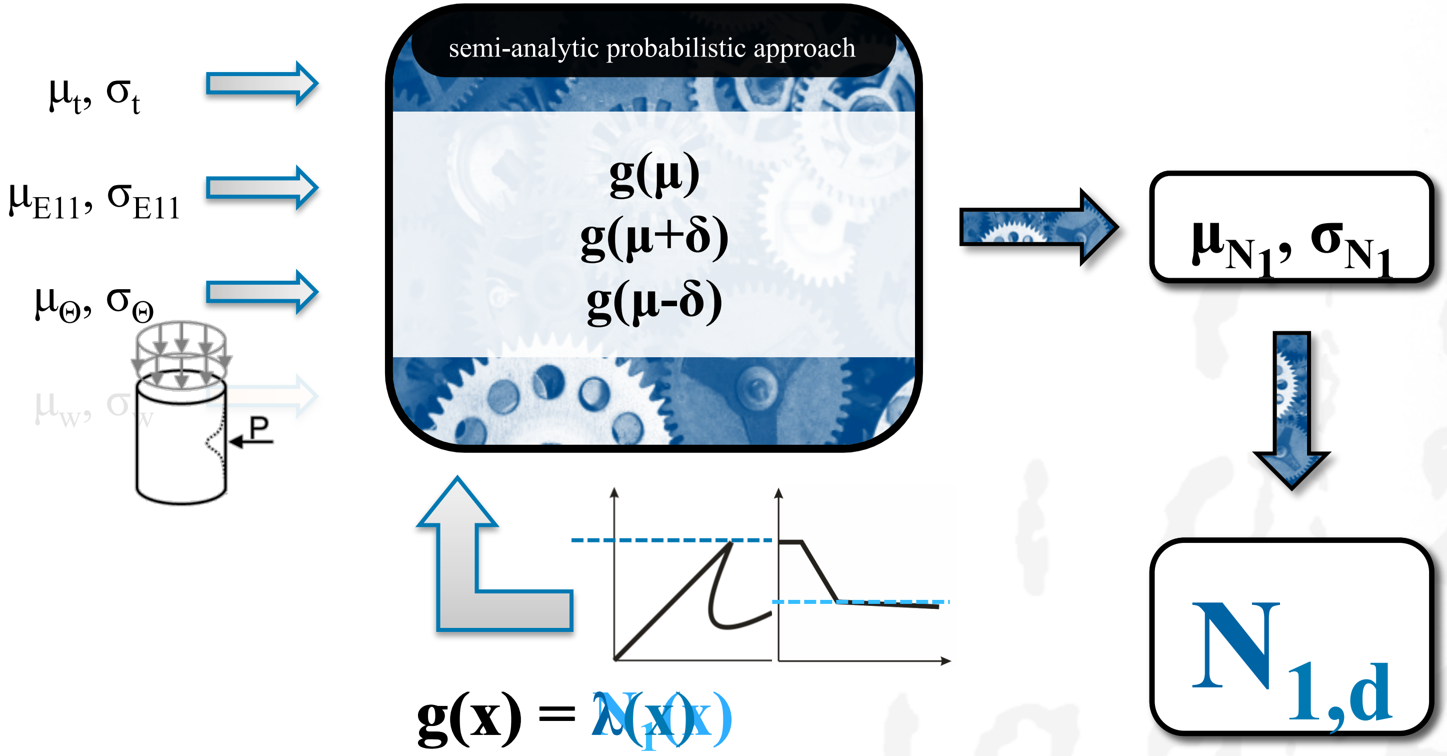


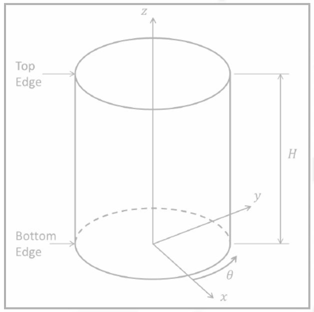
PPLA: Application – Use Cases

PPLA applied to shells treated within DESICOS

- Shell Z15 (DESICOS benchmark shell)
  - nominal thickness t = 0.5 mm
  - free length L = 500 mm, radius R = 250 mm
  - CFRP IM7/8552, [±24 / ±41]

[Degenhardt et al., 2007]

- Shell Z36 (manufactured and tested within DESICOS)
  - nominal thickness t = 0.75 mm
  - free length L = 800 mm, radius R = 400 mm
  - CFRP IM7/8552, [±34 / 0 / 0 / ±53]



PPLA: Application to Z15 – Input Parameters

- Scattering wall thickness
  - Data basis: measurements of Cylinders Z15-Z26
  - Smeared wall thickness derivation for the entire shell
- Scattering material properties
  - Central moments obtained from [Degenhardt et al., 2009]
- Loading imperfections
  - Central moments obtained from [Kriegesmann, 2012]
  - Positioning of loading imperfections uniformly distributed on interval [0° 180°]

μ_t, σ_t

μ_{E11}, σ_{E11}

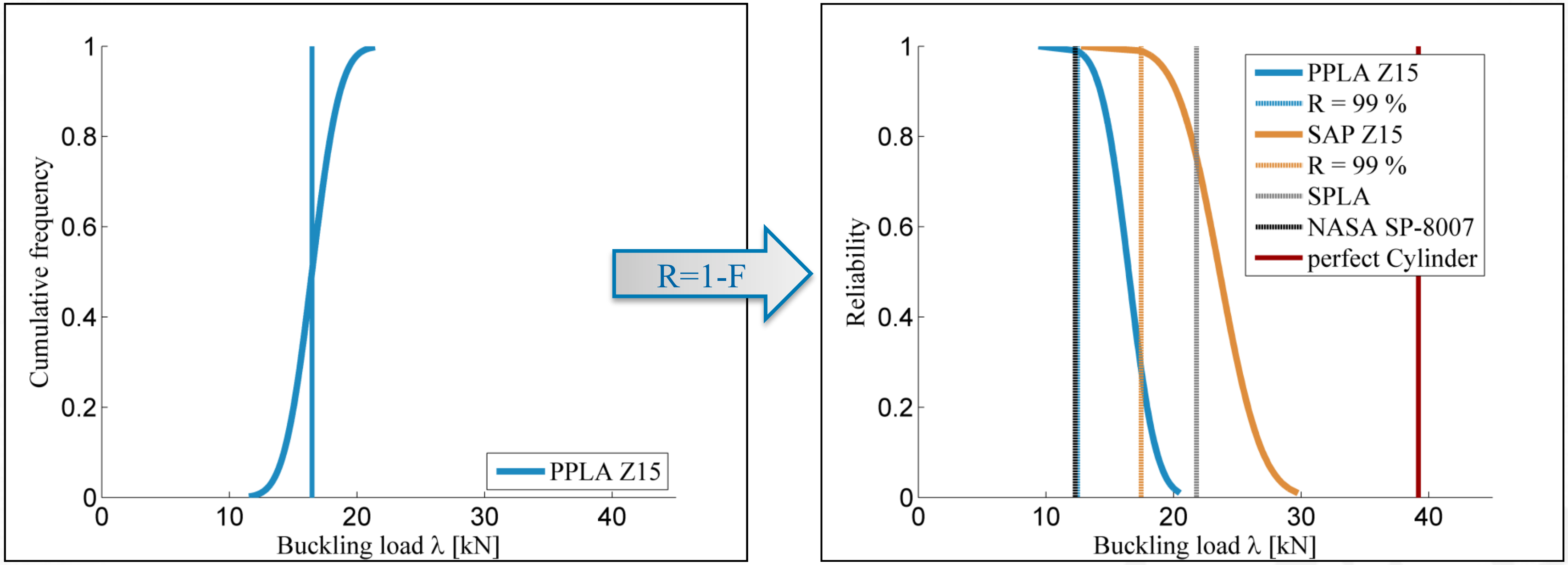
μ_{E22}, σ_{E22}

μ_{G12}, σ_{G12}

$\mu_{\Theta}, \sigma_{\Theta}$

$\mu_{\omega}, \sigma_{\omega}$

PPLA: Application to Z15 – Results



Approach	Reliability	Design load	Knock-Down
PPLA Z15	**99 %**	**12.5 kN**	0.32
SAP Z15	**99 %**	**17.4 kN**	0.44
NASA SP-8007	-	12.3 kN	0.32
	Min. test result	21.3 kN	0.54

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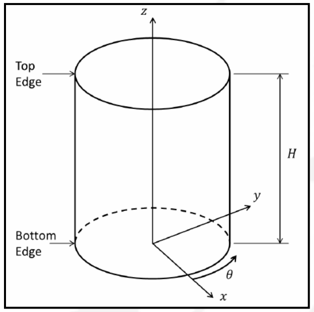


PPLA: Application to Z36 – Input Parameters

- Scattering wall thickness
  - Data basis: measurements of Cylinders Z15-Z26
  - Smeared mean thickness value for every shell obtained from [Degenhardt et al., 2009] leads to

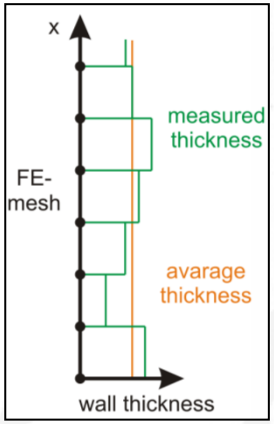
$$\Delta t_{Degenhardt,i} = t_{measured,i} - t_{nom,Z15}$$

  - Predicted mean thicknesses for new laminate setup:

$$t_i = t_{nom,Z36} + \Delta t_{Degenhardt,i}$$

  - Determination of central moments of wall thickness

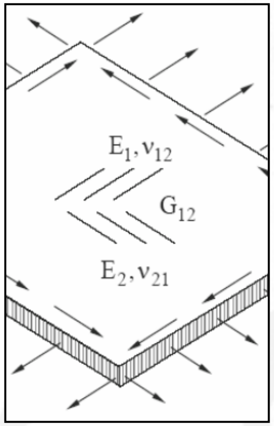
$$\boxed{\mu_t, \sigma_t}$$



PPLA: Application to Z36 – Input Parameters

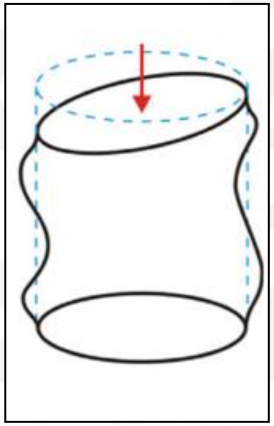
- Scattering material properties
  - Same CFRP material as Z15, thus the ESA study can serve as data basis
  - Central moments obtained from [Degenhardt et al., 2009]

$\boxed{\mu_{E11}, \sigma_{E11}}$ $\boxed{\mu_{E22}, \sigma_{E22}}$ $\boxed{\mu_{G12}, \sigma_{G12}}$



- Loading imperfections
  - Same testing machine as in [Degenhardt et al., 2009]
  - Central moments obtained from [Kriegesmann, 2012]

$\boxed{\mu_{\Theta}, \sigma_{\Theta}}$



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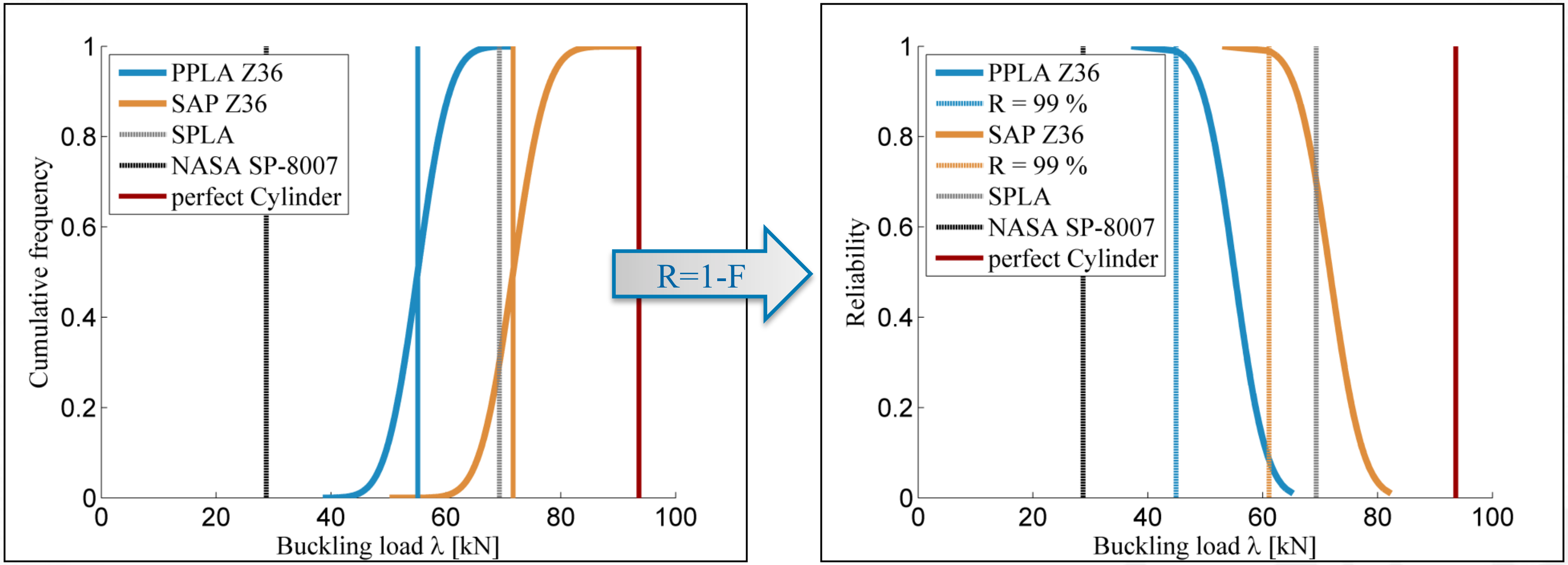
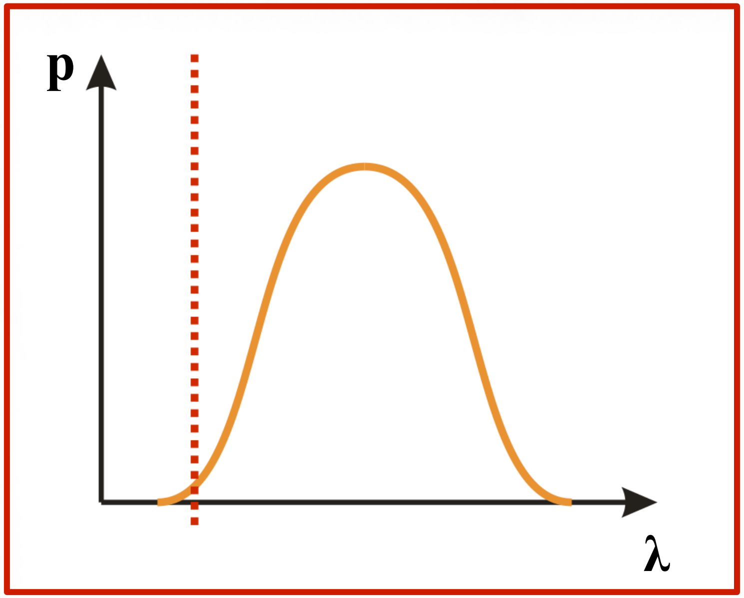
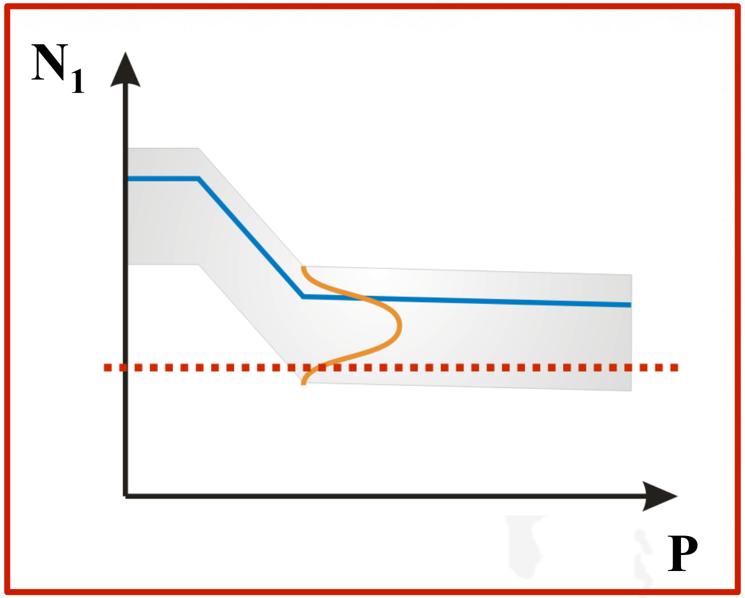


Approach	Reliability	Design load	Knock-Down
PPLA Z36	**99 %**	**44.9 kN**	0.48
SAP Z36	**99 %**	**61.1 kN**	0.65
NASA SP-8007	-	28.7 kN	0.31
	Test result	64.0 kN	0.68

PPLA: Application to Z36 – Results





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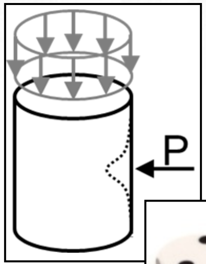
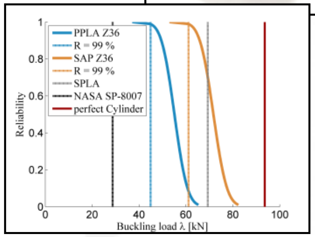
Conclusion and next steps

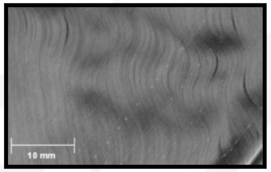
- A combination of the SPLA and a semi-analytical probabilisic procedure has been established
  - geometric imperfections are covered by SPLA
  - non-traditional imperfections are covered stochastically
  - robust design loads were obtained





Future work:

- For which laminate setups is the SPLA applicable?
- Investigations on further non-traditional imperfections
- Comparison of the simulations with experimental results within DESICOS



[Hühne et al., 2008]

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Backup

PPLA – Evaluation of the objective function

- Taylor approximation of the objective function

$$g(\mathbf{x}) = g(\boldsymbol{\mu}) + \sum_{i=1}^{n} \frac{\partial g(\boldsymbol{\mu})}{\partial x_i}(x_i - \mu_i) + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{\partial^2 g(\boldsymbol{\mu})}{\partial x_i \partial x_j}(x_i - \mu_i)(x_j - \mu_j) + \cdots$$

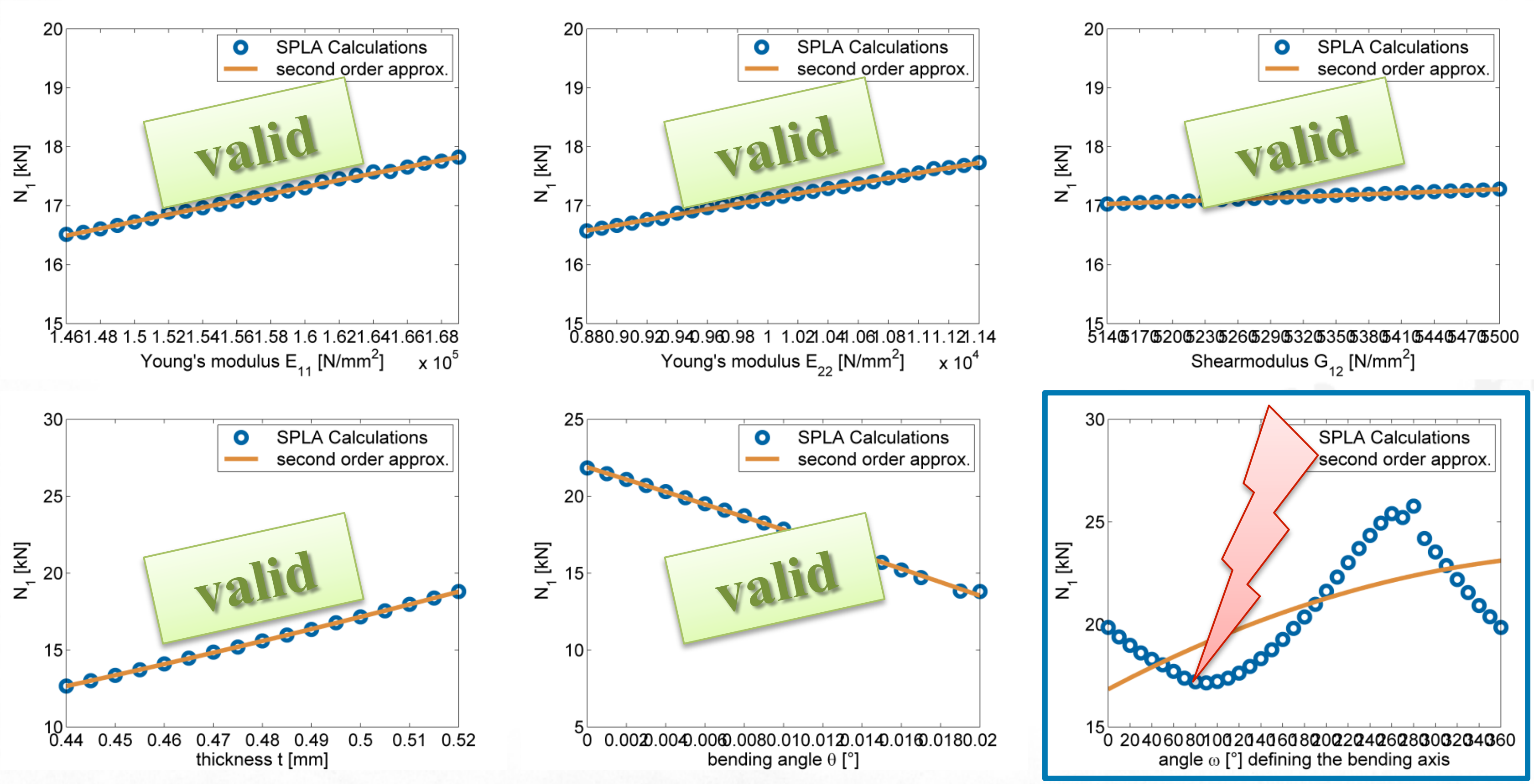
SAP:	$g(\mathbf{x}) = \lambda(\mathbf{x})$	buckling load	✔ [Kriegesmann, 2012]
PPLA:	$g(\mathbf{x}) = N_1(\mathbf{x})$	design load by SPLA	

Is a second order Taylor approximation still valid for $N_1(\mathbf{x})$?

PPLA – Evaluation of the objective function

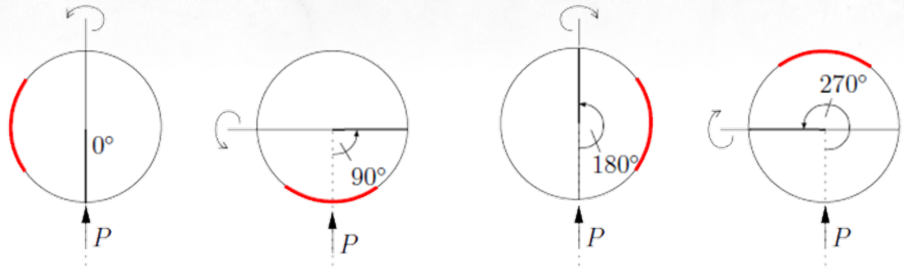
◈ $N_1(\mathbf{x})$ for $x_i = [\mu_{x,i} - 3\sigma_{x,i}\ ;\ \mu_{x,i} + 3\sigma_{x,i}]$

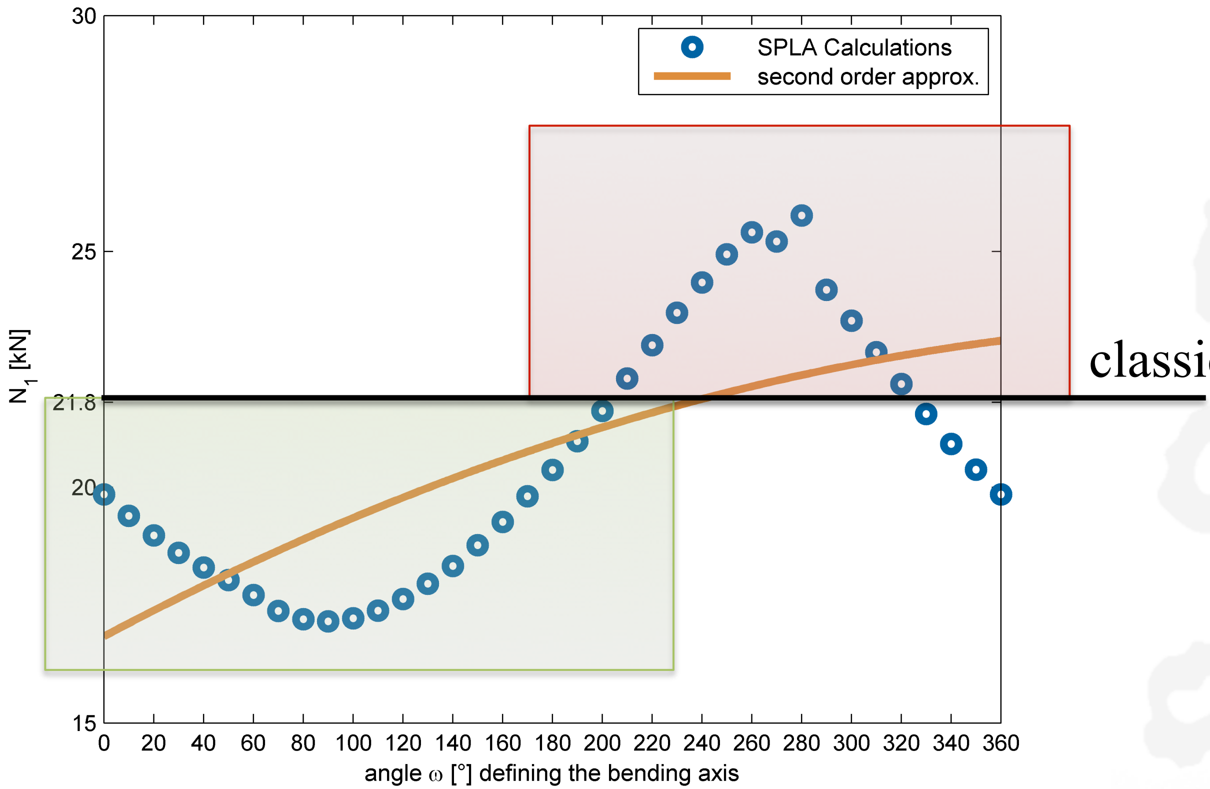
Is a second order Taylor approximation still valid for $N_1(\mathbf{x})$?

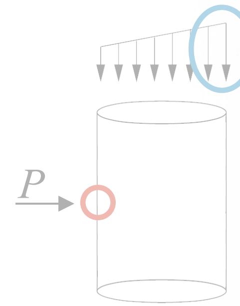


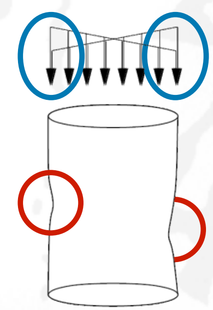
PPLA – Evaluation of the objective function

- $N_1(\omega)$









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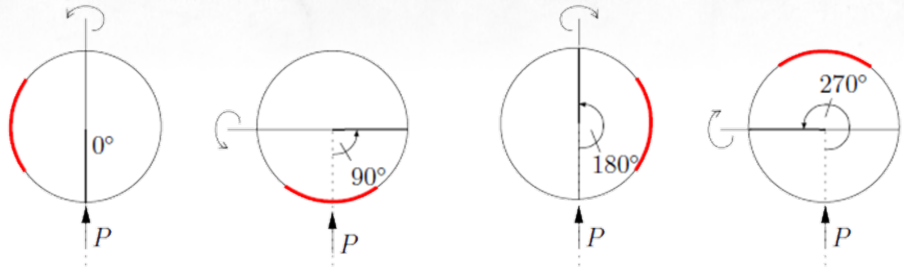

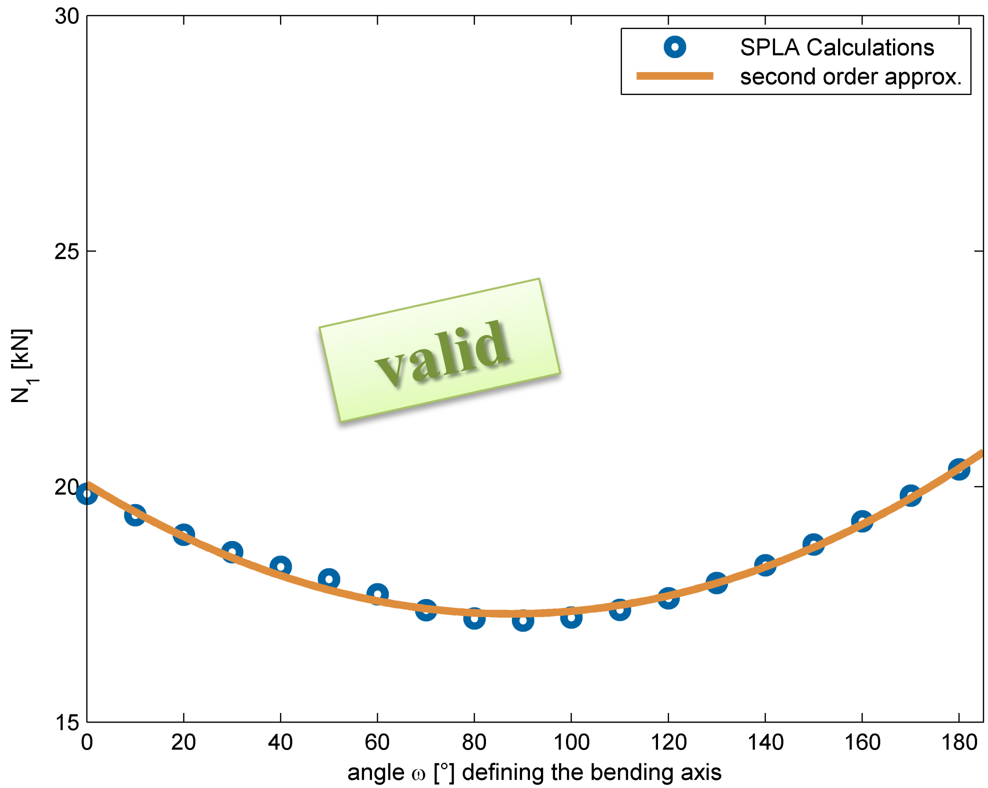

Is a second order Taylor approximation still valid for $N_1(\mathbf{x})$?